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STUDY OF THE MIXTURE-RATIO DISTRIBUTION IN THE DROPS

OF SPRAY PRODUCED BY IMPINGING LIQUID STREAMS

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SUMMARY

A colorimetric method was employed to determine the mixture ratio of the individual drops in the spray of three types of injector. The distributions, mixture ratio against number of drops, and mixture ratio against spatial location, were determined for each injector. The three injectors, in order of decreasing mixing efficiency, were the triplet, the impinging jet, and the swirl cup. Mixture ratio varied appreciably for a given injector as well as among different injectors.

INTRODUCTION

Propellant mixing is one of the fundamental parameters in rocket combustion that has received little attention. For combustion to occur the propellants must be mixed at some stage in the combustion process. Many times the performance of a combustor can be explained by the amount of mixing achieved by the injector (Ref. 1). The extent of mixing may contribute to other phenomena in rocket engines such as combustion instability (Ref. 2) and local burnout as well as the over-all performance. In the case of hypergolic liquid propellants, mixing becomes especially important if one desires to take advantage of liquid-phase reactions that may occur with these systems.

Rupe (Ref. 3) evaluated the time average - spatial distribution of mixture ratio for an impinging-jet type injector over a wide range of geometry and flow ~~variables~~. In another study, mixing efficiency was determined by

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measuring the temperature rise of an acid-base reaction where mixing efficiency was given by the percent of theoretical temperature rise (Ref. 4). Since all injectors ultimately produce droplets of propellants, it seems desirable to determine the degree of mixing in individual drops. As mentioned previously, this determination would be more important when one is dealing with liquid-phase reaction. For a miscible liquid-propellant system, mixing may be defined as the distribution of propellants among the drops produced by the injector. Perfect mixing would be achieved if the input mixture ratio occurred in each drop.

A preliminary study was therefore undertaken to evaluate a colorimetric method for determining the mixture ratio in individual drops. The mixing efficiency of the injector was obtained from a random sampling of the collected drops. Three injectors, a triplet, an impinging jet, and a swirl cup were evaluated at one flow condition using miscible fluids. The data are compared in three ways: spatial distribution of mixture ratio, distribution of mixture ratio among drops, and finally the mixing efficiency of the injectors was obtained.

EXPERIMENTAL

Technique and Instrumentation

Propellants were simulated in this study by aqueous dye solutions. A discussion of the principles of colorimetric analysis may be found in Ref. 5. Essentially the solutions should follow Beer's law and each solution should absorb light at the wavelength of maximum transmission of the other. Filters are then selected to give the wavelengths corresponding to maxima of transmission of the two solutions. If the transmission at each wavelength is measured for a series of mixtures of known ratio, a calibration curve such as that in Fig. 1 may be obtained. It is seen that measurement of transmission at each wavelength uniquely determines the mixture ratio of an unknown mixture.

A block diagram of the colorimeter is shown in Fig. 2. The instrument was a Leeds & Northrup microdensitometer with provisions for adding filters. The sample holder consisted of two sheets of Lucite spaced 0.025 inch apart that also served to flatten the drop surfaces normal to the light beam. The optics of this system introduce a lower limit of drop diameter that can be measured; however, this limitation can be overcome by dilution of the drop with water to the minimum size. Dilution has no effect on the mixture ratio. It does, however, decrease sensitivity since the curves converge with increasing dilution, as shown by Fig. 1. The two dyes used were a green dye (Brilliant Green) and a yellow dye (Proflavine Sulfate). The filters were a Wratten No. 16 (yellow) and a liquid filter using the green dye solution.

A sample of the drops in the spray of each injector was obtained by means of the shutter mechanism also shown in Fig. 2. The drops were collected on a 20-inch-square greased plate so that their individual identity was maintained. A series of perpendicular grid lines 1 inch apart were scribed on the plate to obtain spatial location of the drops. An average of about 25 percent of the drops in each square was selected at random for analysis. The sampling distance was 12 inches in each case.

Injectors

The three injectors studied were a triplet, an impinging jet, and a swirl cup. Their dimensions are shown in Fig. 3. These designs are typical of those used in many rocket combustion studies. Each injector was operated at a pressure drop of 45 pounds per square inch, giving input flow ratios, green to yellow, of 1 except for the swirl cup, which had an input ratio of 2. These flow ratios are based on calibrations of the flow rates. The patterns formed by the spray on the collection plate are also indicated.

RESULTS AND DISCUSSION

Spatial Distribution

Each spray was found to have an axis of symmetry with respect to mixture ratio indicated as the x-axis in Fig. 3. Thus along lines of constant x-distance there was only a random variation in mixture ratio. Along lines of constant y-distance, however, a continuous variation in mixture ratio was found that was readily explained from the injector geometry. This variation is shown in Fig. 4 where the average mixture ratio (percent green) is plotted as a function of distance from the y-axis. Each point represents the average value of mixture ratio of the drops in an area bounded by the total y-distance and a 1-inch increment of x-distance. The standard deviation of the data was computed for each x-station, and since these values did not differ greatly, they were averaged. Thus, the standard deviations were 8.3, 5.7, and 6.9 percent green for the triplet, impinging jet, and swirl cup injectors, respectively. The triplet produces a symmetric spatial distribution with the largest amount of yellow component appearing at the center, corresponding to its plane of injection. For the other injectors, there is a continuous decrease in mixture ratio as the spray is traversed with the nominal input ratio occurring near the center. The integrated average mixture ratios obtained from experimental data agreed reasonably well with the nominal input ratios obtained from flow calibration. Nominal ratios (percent green/percent yellow) were 50/50 for the triplet and impinging jet and 67/33 for the swirl cup, while the experimental averages were 44/56 and 62/38, respectively. For the impinging jet injector, interpenetration of the two streams occurred, so that higher concentrations of the components appeared in the spray on the side opposite to that of injection.

The configuration of the swirl-cup injector presumably imparts an angular motion to the liquids, so that the axes of the spray pattern would depend on sampling distance. The orientation of injector and spray pattern shown previously in Fig. 3 was observed at 12 inches. A hollow-cone spray is typical of this injector type. The mixture ratio about the annular section varied sinusoidally. Starting at $x = -1$ and proceeding clockwise, the percent green was a maximum at 0° and a minimum at 180°, while the input ratio occurred at 90° and 270°.

Mixture-Ratio Distribution among Drops

The distribution of drops with respect to mixture ratio is shown in Fig. 5 for each injector. According to the stated definition, if mixing were ideal, all drops would have the input mixture ratio. From Fig. 5, the triplet injector approaches ideality most closely. The swirl cup produced drops in two ranges, each rich in one of the components, while the impinging jet was intermediate, giving a relatively flat distribution.

Mixing Efficiency

If it is assumed that the direction of deviation of mixture ratio (i.e., richer or leaner) from the input ratio has no significance, it is possible to arrive at a mixing efficiency for each injector by considering what fraction of the material in a drop is in the input ratio. The following equations, also given in Ref. 3, give the percent mixed in individual drops:

$$\text{Percent mixed} = 100\left[1 - \left(\frac{R - r}{R}\right)\right], \quad r < R$$
$$= 100\left[1 - \left(\frac{R - r}{R - 1}\right)\right], \quad r > R$$

where R is the nominal input mixture ratio expressed as fraction of green and r is the mixture ratio in the given drop expressed in the same way.

Figure 6 shows the fraction of total drops as a function of their percent mixed for each injector. Ideally, all drops should be at 100 percent. The average values of percent mixed (mixing efficiency) also indicated in the figure, show the triplet to give the highest mixing efficiency (85 percent) followed in order by the impinging jet (68 percent) and swirl cup (55 percent). The 68 percent value for the impinging jet is of the same order as that found in Ref. 3. A previous evaluation of the mixing efficiency using the temperature-rise method gave a value of about 70 percent for the swirl cup (Ref. 2). These data were obtained at pressure drops of about 200 pounds per square inch compared with 45 pounds per square inch in the present study. It is likely that this additional energy would improve mixing.

CONCLUDING REMARKS

The liquid-phase mixing of three injectors was studied by determining the mixture ratio occurring in individual drops of the sprays. The colorimetric technique used to measure mixture ratios seems to be satisfactory.

The results show that appreciable differences may be found in the way the various injector types mix and distribute the injected fluids. The injectors in decreasing order of mixing efficiency were a triplet, an impinging jet, and a swirl-cup or premix type. Knowledge of these distributions should materially aid in the interpretation of rocket combustion phenomena when applied to a specific propellant combination or a specific combustor. For example, with hypergolic propellants, ignition may proceed more smoothly at a mixture ratio considerably different from that of optimum performance for which injectors are generally designed. The obtaining of satisfactory ignition under such conditions may be due in part to the wide range of mixture ratios found to exist in the drops of spray produced by the injector.

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FIGURE LEGENDS

Fig. 1. - Typical calibration curve.

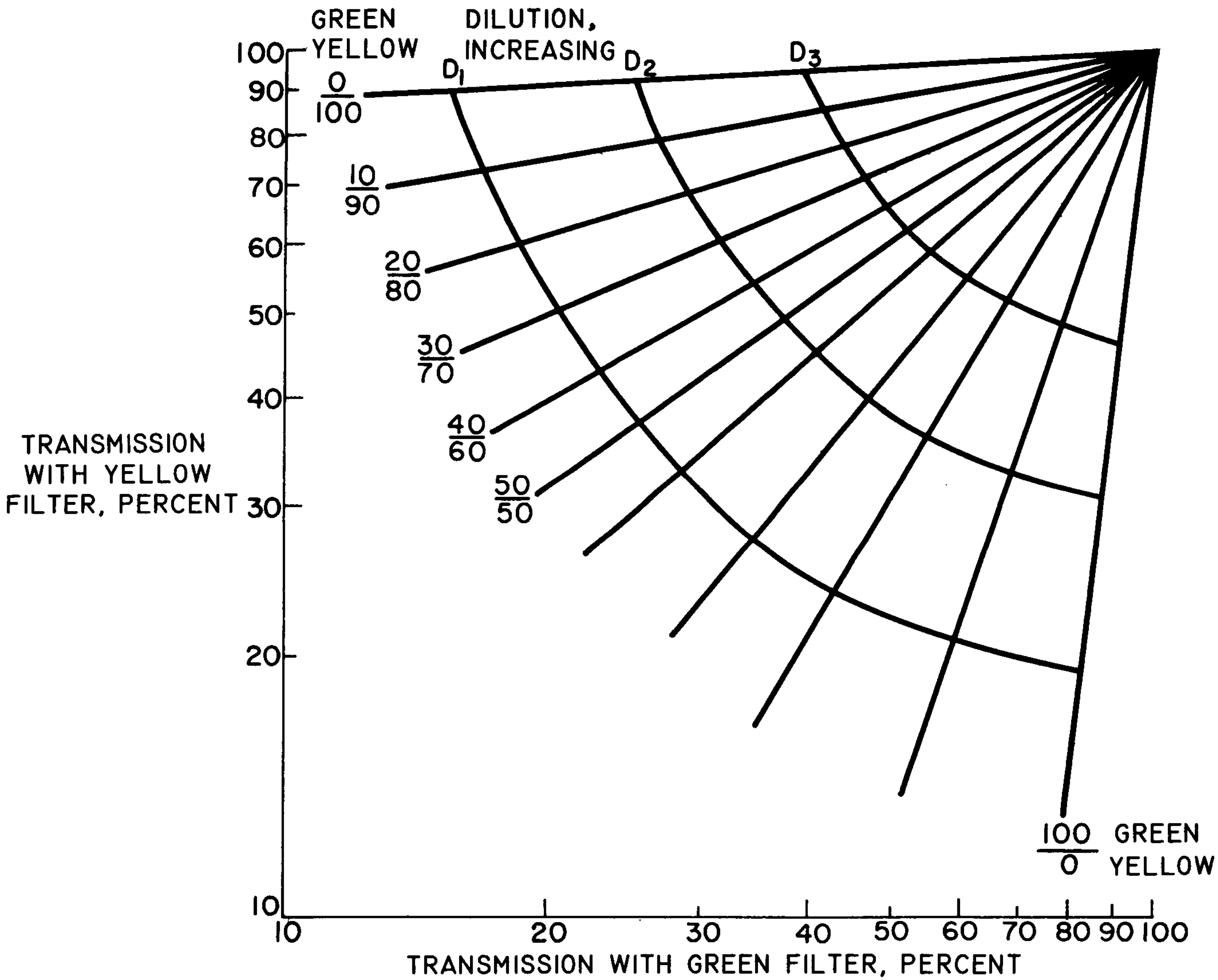
Fig. 2. - Apparatus.

Fig. 3. - Injectors.

Fig. 4. - Spatial distribution of mixture ratio.

Fig. 5. - Mixture ratio distribution among drops.

Fig. 6. - Mixing efficiency distribution among drops.



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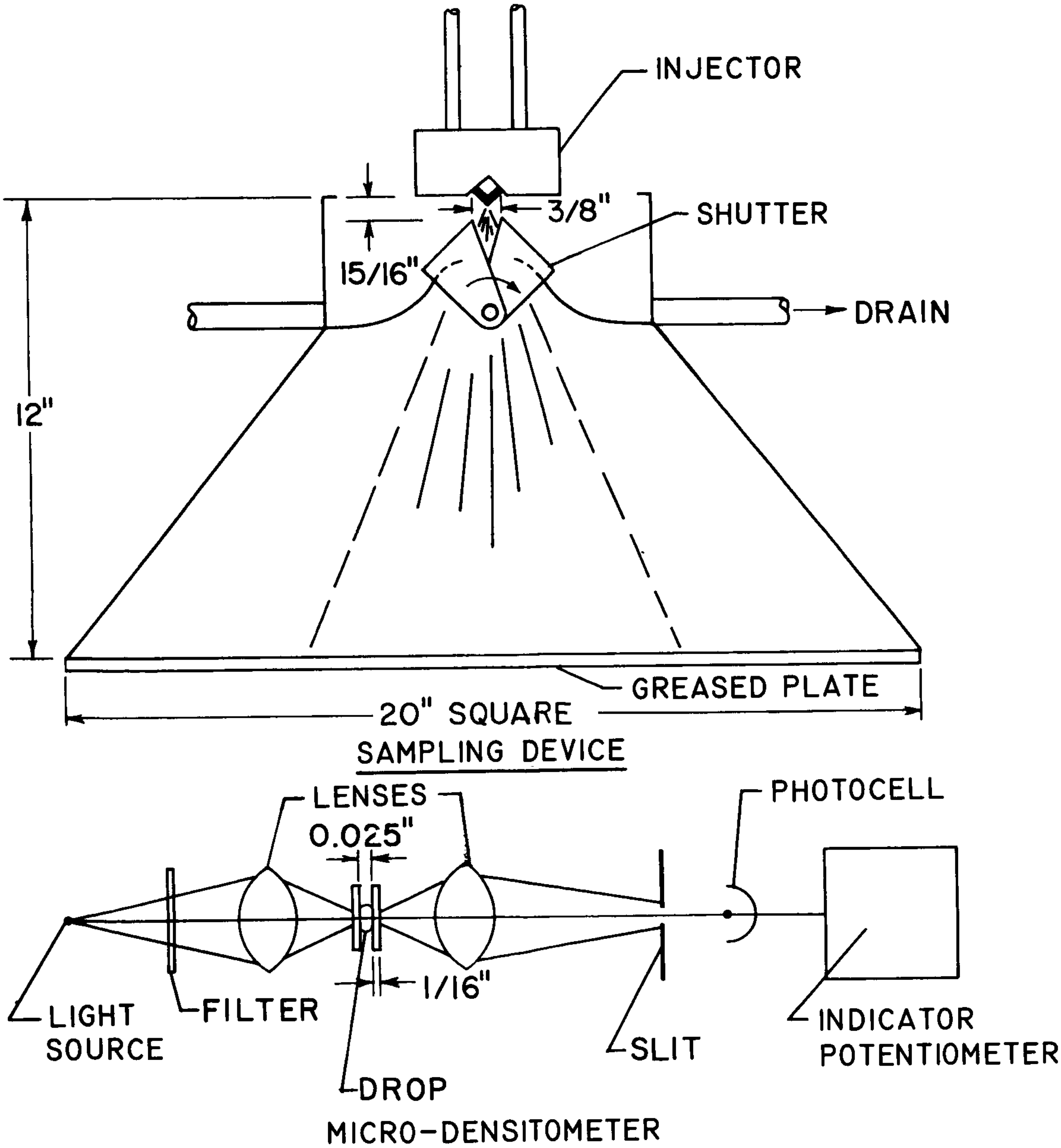

Fig. 2. - Apparatus.

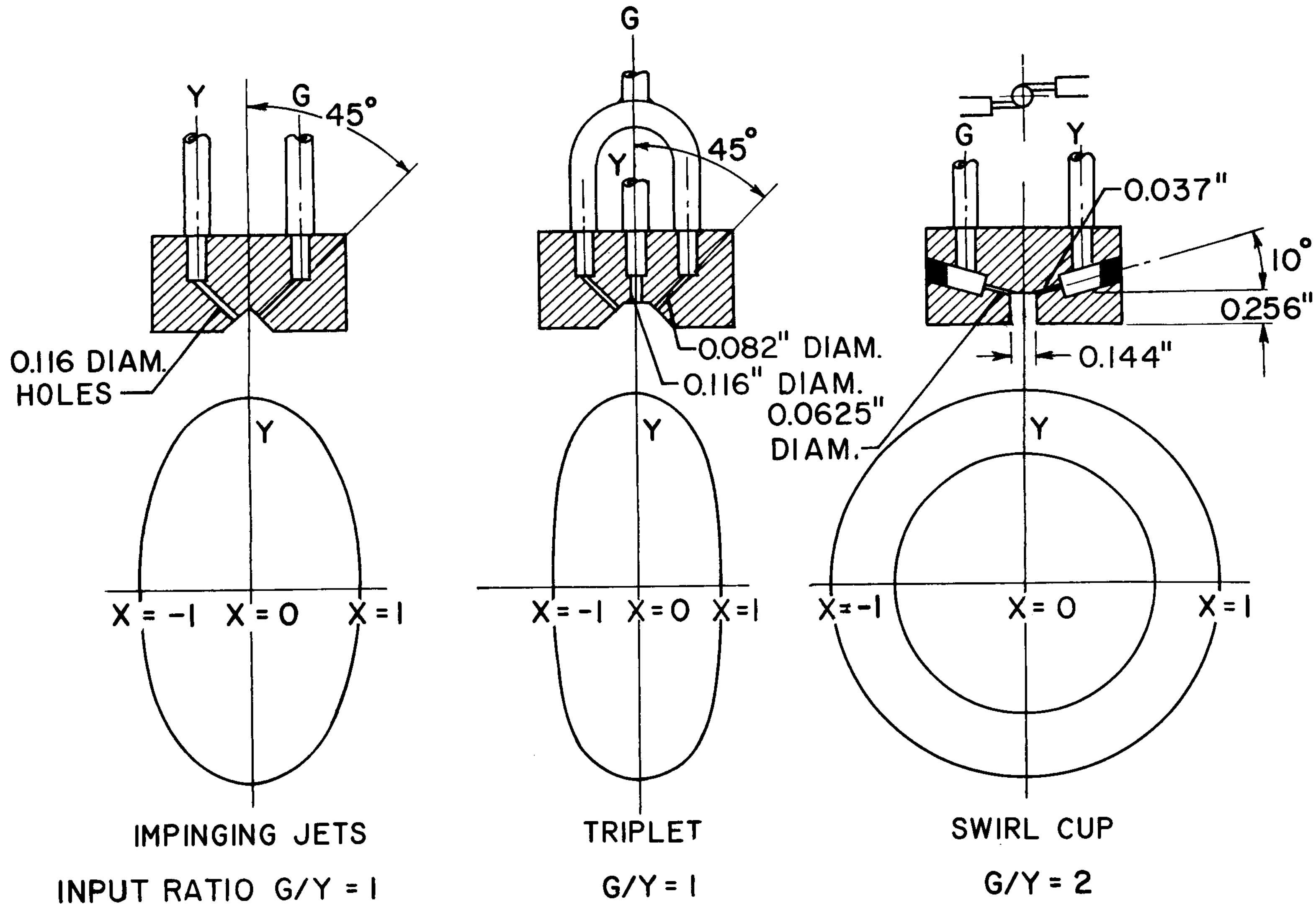

Fig. 3. - Injectors.

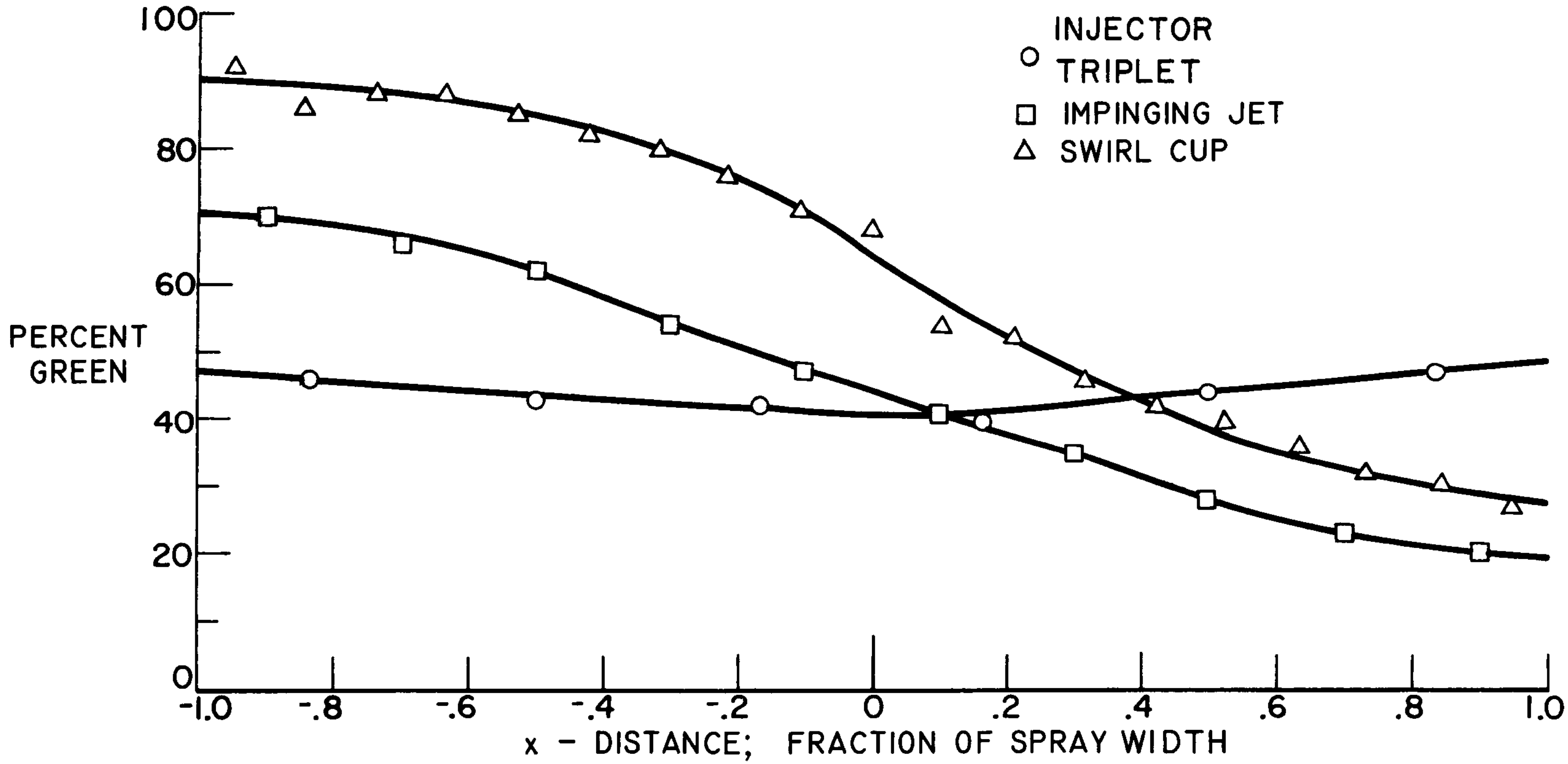

Fig. 4. - Spatial distribution of mixture ratio.

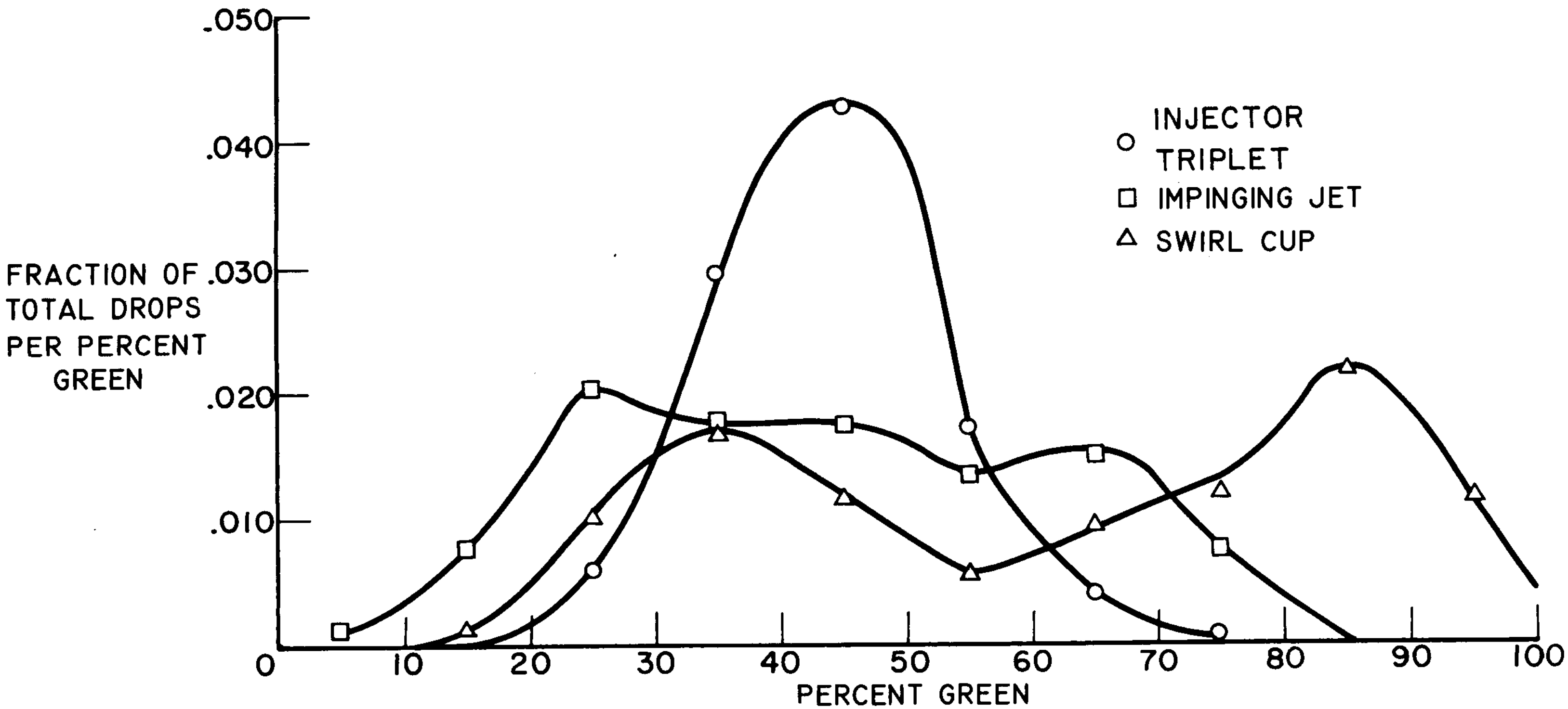

Fig. 5. - Mixture-ratio distribution among drops.

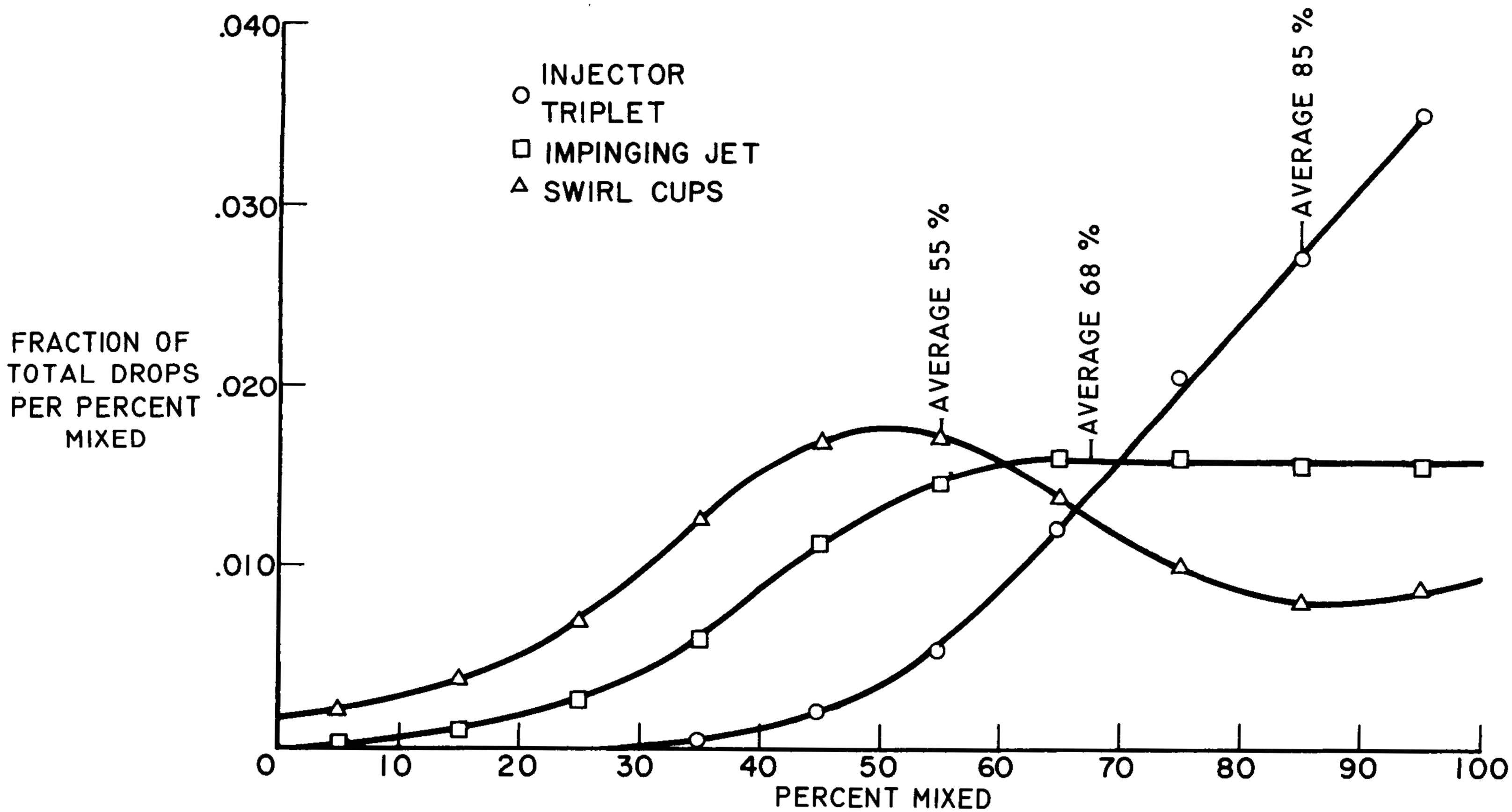

Fig. 6. - Mixing-efficiency distribution among drops.